U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL OCEAN SERVICE

Data Acquisition and Processing Report

Type of Survey Hydrographic Lidar

Project No. OPR-H355-KRL-11

Time frame October – November 2011

LOCALITY

State Florida

General Locality Florida Keys National Marine Sanctuary

2011

HYDROGRAPHER	**CHIEF OF PARTY**
SCOTT RAMSAY	JOSE MARTINEZ-DIAZ

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DATE

NOAA FORM 77-28 (11-72) U.S. DEPARTMENT OF COMMERCE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

HYDROGRAPHIC TITLE SHEET

REGISTRY No. **H12377 – H12384**

State Florida

General Locality Florida Keys National Marine Sanctuary

Scale 1:10,000 **Date of Survey** October 7 to November 15, 2011

Instructions dated April 29, 2011 **Project No.** OPR-H355-KRL-11

Vessel Dynamic Aviation Aircraft, call sign N89F

Hydrographer S.R. Ramsay **Chief of Party** J.V. Martinez-Diaz

Surveyed by J.W. Croucher, R.J. Pritts, D.D. Johnson, M.H. Blackbourn, K.H. Kline, M.J. Cox, N.M. Clark

Soundings by SHOALS-1000T

Graphic record scaled by M.H. Blackbourn

Graphic record checked by S.R. Ramsay, J.V. Martinez-Diaz **Automated Plot** N/A

Verification by

Soundings in Meters at MLLW

REMARKS

Requisition / Purchase Req. # NCNJ3000-11-02857

Contractor Fugro LADS, Inc., 2113 Government St., Suite I, Ocean Springs, MS 39564

Sub-Contractor Fugro Pelagos, Inc., 3574 Ruffin Rd., San Diego, CA 92123

JOA Surveys, LLC, 12001 Audubon Dr., Anchorage, AK 99516

Times All times are recorded in UTC.

Datum and Projection NAD83, UTM (N) Zone 17

Purpose The purpose of this survey is to provide NOAA with modern, accurate hydrographic survey data with which to update the nautical charts of the assigned area.

Acronyms A complete list of all acronyms used throughout this report is provided at Appendix I of the Separates Report.

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A. EQUIPMENT

Fugro Pelagos, Inc. (FPI) operates the SHOALS-1000T Airborne Lidar Bathymetry (ALB) system, which is comprised of two main subsystems. The Airborne System (AS) is used to acquire raw bathymetric data, real-time inertial and Global Positioning System (GPS) data and downward-looking digital imagery. The Ground Control System (GCS) is used to plan operations, calculate depth values from the raw data, apply post-processed kinematic GPS (KGPS) positioning, apply tidal corrections, provide tools to allow the collected data to be evaluated and export digital data for the compilation of final survey deliverables. These two subsystems are complemented by other tools required for quality control activities; in particular, Fledermaus visualization of vertical standard deviation, density and 3-D bathymetric surfaces. Third party software is also used for product compilation, imagery and reflectance data creation, and survey management, namely CARIS, ERDAS and ENVI. The general data flow between the subsystems and tools is illustrated in Figure 1.

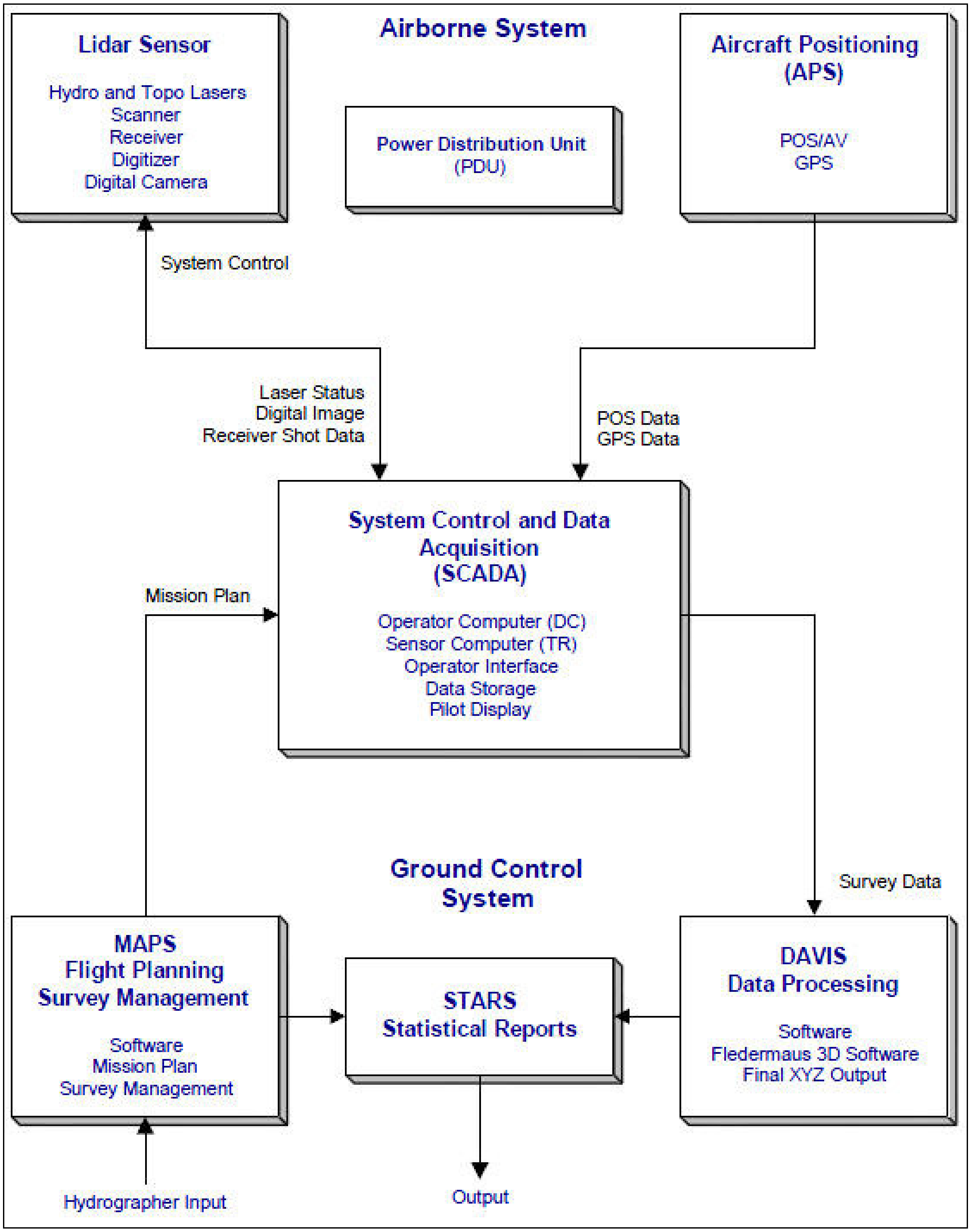


Figure 1 – General data flow within the FPI ALB system

A.1 AIRBORNE SYSTEM

The SHOALS-1000T ALB system is capable of acquiring 1,000 soundings per second in bathymetric mode. SHOALS soundings are acquired by the transmission of laser pulses from the aircraft through a scanning system and detecting return signals from land, the sea surface, the water column and the seabed. The scanning (transmitting) occurs on a stabilized platform that compensates for aircraft pitch and roll. The return signals are electronically amplified and conditioned prior to being digitized and logged.

Figure 2 – The FPI SHOALS-1000T ALB System

The SHOALS-1000T can be configured to operate at many different sounding densities, namely 2m x 2m, 3m x 3m, 4m x 4m and 5m x 5m spot spacing. A 2m x 2m sounding density is typically used for engineering applications, where higher resolution may be required, whereas a 5m x 5m sounding density is typically used for larger scale, lower-resolution mapping requirements, such as resource planning. All sounding densities meet the IHO Order 1 Depth and Position accuracy requirements. For OPR-H355-KRL-11 the 4m x 4m sounding density was utilized and all seabed areas were flown on at least two separate occasions (200% coverage).

The survey platform for the SHOALS-1000T AS throughout this project was Dynamic Aviation's Beechcraft King Air A90, call-sign N89F.

Figure 3 - Dynamic Aviation's Beechcraft King Air A90

Aircraft Type:	**Beechcraft King Air A90**
Aircraft Endurance	4.5 hours (average)
Aircraft Range	up to 1000 nautical miles
Aircraft Transit Speed	175 knots
Aircraft Transit Altitude	7,500 to 9,000'
Survey Configuration	altitude 1000-1300'
Airborne System	– Independent sensor cooling – Gyro stabilized scanner bed – single operator console – integrated heads up pilot display
Operational Capability	full day or night operation, all weather (VFR, IFR)
Airborne Survey Crew	1 operator, 2 pilots
Depth Sounding Rate	1000 soundings per second
Depth Range	to 50 m dependent on water clarity
Topographic Range	to 150 m above sea level
Sounding Density	2 x 2 m, 3 x 3 m, 4 x 4 m and 5 x 5 m
Swath Width	Variable swath, up to 0.58 x altitude
Digital Imagery Capability	DuncanTech, high res RGB with digital gain and exposure control
Position Systems	Real-time WADGPS and post-processed KGPS
Horizontal Accuracy	IHO Order 1
Vertical Accuracy	IHO Order 1
Area Coverage	50.4 km^2 per hour, 4 x 4m
Ground Control System	Fully transportable system for planning, data processing and review

Table 1 – Aircraft and SHOALS-1000T Operating Specifications

A.1.1 Flight Planning

FPI develops all line plans using the SHOALS GCS software suite. The software is capable of importing a vector file of the project boundary as well as shoreline and other information. The line plans were generated to maximize efficiency of flight while maintaining the survey requirements set forth in the Hydrographic Survey Project Instructions.

One limitation of the GCS software is that only one operator may have access to a 'Block' of flight lines once the data has been collected. Thus, the project area was divided into 4 separate blocks vertically. In order to manage expected variable water clarity conditions it was also decided that the area should be divided horizontally in to a western and eastern section. This incurred additional aircraft turn times between successive flight lines, but resulted in far fewer refly lines for poor water clarity. The result was eight GCS Blocks, aligned with the NOAA registered sheet limits, as described in the following graphic:

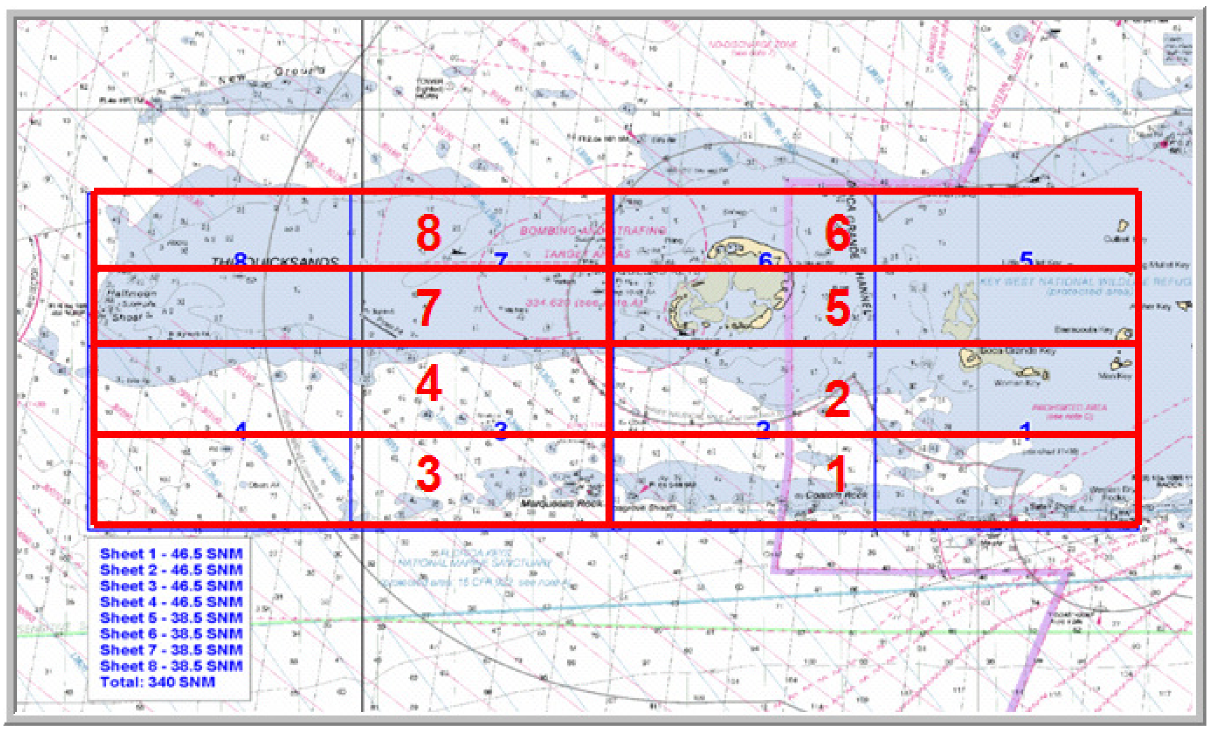


Figure 4 – GCS 'Blocks' for Data Acquisition and Processing

Prior to the commencement of operations Air Traffic Control at Key West International Airport was contacted to discuss the project area and timing of airborne operations. Permission was also sought and authorized to establish tide gauges within, and operate an aircraft over, the Florida Keys National Marine Sanctuary and Key West National Wildlife Refuge.

A.1.2 Positioning Equipment

Throughout the survey real-time positioning of the SHOALS-1000T system was derived from an integrated Trimble receiver with differential GPS corrections from a Fugro Omnistar receiver (Wide Area DGPS mode). Post-processed positioning was achieved by simultaneous data logging, with Novatel DL-5 dual frequency GPS receivers at the FPI BASE reference station and onboard the aircraft.

The FPI BASE reference mark was established at the Key West International Airport. The FPI BASE reference station recorded data at a 1.0 second interval for the duration of the airborne collection. The FPI BASE data was processed against the logged aircraft GPS using Applanix POSPac, to accurately solve for the position of the laser source throughout each flight.

Following all dynamic and static GPS data processing with Applanix POSPac 5.4 the following quality factors were assessed to determine if the final GPS solutions adhered to the project accuracy specifications:

- Dilution of Precision – PDOP, HDOP, and VDOP
- Position Accuracy – RMS for Easting, Northing and Height
- Float / Fixed Ambiguity Status – ambiguity status for each epoch
- Number of Satellites

Depending on the magnitude of errors, some flight lines were reflown to improve the final data accuracy.

A.1.3 Sortie Control

Mission Plans were generated from the flight planning software, which were then imported into the airborne sensor via a compact flash memory card. Several Mission Plans were accessed during the course of a flight in order to perform absolute and relative accuracy checks and to optimize the data collection over the clearest possible water conditions.

The Airborne Operator selects each survey line for data collection and ensures that the automatic line specs meet the target parameters for the project. Through the airborne operator interface and the acquisition software, the Airborne Operator has the ability to modify an existing line, or create a new line should the need arise. During the sortie the lidar and position data are logged to a compact flash card, which is easily transferred and downloaded onto the field server.

Data was only collected when environmental conditions were suitable. To be specific, the following conditions had to exist prior to launch of the aircraft:

- The project area was cloud-free below the design altitude for the mission (1300ft).
- The area was free of smoke or haze.
- Wind strengths were below 25 knots.
- Air traffic restrictions were accounted for.

Laser Power Timing Tests (LPTT) were conducted at the start and end of every sortie. During this test, the laser is directed through a fiber optic cable of fixed, known length and the timing measured to confirm proper operation of the system. These data were analyzed and logged after each flight using the GCS software to ensure data was within acceptable thresholds. Results were stored in the LPTT Log.

For each test the APD, IR and Raman channels did not differ from the expected value by more than +/- 0.5ns. The PMT channel exhibited more of a variation, however it did not regularly exceed +/-0.7 ns.

A.1.4 Ancillary Equipment and Data

The SHOALS-1000T contains an integrated digital camera, which provides geo-referenced images of the coverage being flown. This not only makes data processing and editing much simpler, it provides an additional data product based on the digital photography acquired during each flight. This imagery was geo-referenced, ortho-rectified and mosaiced to produce high quality orthophotography of the survey area. The sophisticated airborne GPS/IMU system and the relatively low flying heights produce a pixel resolution of 20-30cm (depending upon flying height).

The SHOALS-1000T was also used for seabed imaging, as it is capable of producing lidar seabed imagery. These estimates of seabed reflectivity are derived through the inversion of the bathymetric lidar equation and measurement of the bottom peak signal of each waveform. This results in relative reflectance imagery that looks similar to that of sidescan sonar interferrometry or multibeam backscatter, and can be used to identify homogeneous areas of seabed. This means that one can now use airborne lidar bathymetry to draw conclusions about bottom type and seabed habitat, in addition to simply measuring water depths. It should be noted that the SHOALS-1000T can produce “absolute” reflectance, and not just relative reflectance, for more accurate seabed classification.

A.2 GROUND CONTROL SYSTEM

Conversion of raw sounding data from the AS to final depth data was accomplished on the field Ground Control System server. This field server was connected to four operator terminals, with all applicable software installed and stringent data archival processes in place. At critical points during the data collection phase full project data saves were conducted and backup media dispatched to the FPI office in San Diego. At the conclusion of field operations a full final field-save was conducted and all copied data transferred to the main computer servers at the FPI office, for in-depth data verification.

All acquired bathymetric lidar data went through an in-field *preliminary* review to assure that adequate coverage had been obtained and that there were no gaps between flight lines or errors in the data before the flight crew departed the project site.

Following each sortie the flight data was run through a complete iteration of processing to ensure that it was complete, uncorrupted, and that the project area has been covered adequately. There are essentially five steps to this in-field data verification:

A.2.1 SHOALS GCS Processing

All SHOALS-1000T data was processed using the Optech SHOALS Ground Control System (GCS) v6.32 on Windows 7 workstations. GCS includes links to IVS Fledermaus v7 software for data visualization and 3D editing and to Applanix POSPac v5.4 software for KGPS positioning processing. GCS program's DAViS (Download, Auto-processing and Visualization Software) module is used to download raw SHOALS sensor data, apply the inertially-aided KGPS solution, auto-process waveforms, with specialized algorithms for surface/bottom detection and depth determination, perform waveform analysis for reflectance generation, and make an initial assessment of data quality. KGPS processing mode was initially used to verify data quality and to perform the large majority of data editing. At a later stage, water level information was applied to validated lidar depths for final survey datum reduction.

A.2.2 GPS Processing

For each flight, a KGPS navigation solution was processed in Applanix POSPac software. GPS data from the airplane and ground control base stations were input in a POSPac project and post-processed to obtain an optimal inertially-aided KGPS navigation solution. In general, the best possible KGPS solution would present a small separation difference between forward and reverse solutions when combined, ideally <0.10 m RMS and remain fixed throughout the flight period. The final smoothed best estimated trajectory (SBET) was then used by GCS during lidar auto processing.

A.2.3 Auto Processing

The auto processing operation (AP) is the core of the GCS software. The AP algorithms incorporate the defined calibration parameters, the optimal environmental settings selection, and the KGPS solution (or tides water level). The AP routines contain a waveform analysis algorithm that detects and selects surface and bottom returns from the raw data. In KGPS mode, raw lidar depths are referenced as absolute ellipsoidal heights. In Tides mode, depths are the relative range between sea surface and the bottom detection. In both modes, waveforms are analyzed to produce raw reflectance data records.

For this project, sea surface detection method (surface logic) was set as Infrared-Raman-Green. This means the surface detection occurred initially using the IR channel. If no IR surface was found then the Raman channel would be used, and then the green channel as last resource. The bottom detection mode always used the green channel in the ‘first pulse’ logic, one that takes into account depth hits that could be flagged as potential targets. The alternate choice of *strongest-return* would have resulted in small objects on the seabed going undetected by GCS.

After AP was complete for a flight mission, the dataset was prepared for editing and validation in Fledermaus software and its 3D editing capabilities.

A.2.4 Lidar Data 3D Visualization

A 3D surface was also rendered during auto-processing. The data was reviewed in Fledermaus for preliminary quality and coverage. As part of the QC process waveform and metadata analysis on a point by point level was reviewed to better determine the quality of the data (refer to Figures 5 and 6). Also during this phase the downward looking imagery was viewed and used to correlate shallow and drying features in the lidar data (refer to Figure 7).

A.2.5 Data QC and Rough Cleaning

In Fledermaus 3D Editor erroneous soundings were deleted and shoal soundings verified. Once rendered, the individual datasets were combined with other adjacent data sets for overlap comparisons, cross check comparisons, and continuity checks. The Lead Hydrographer reviewed these larger areas of data to ensure validity and to plan reflies.

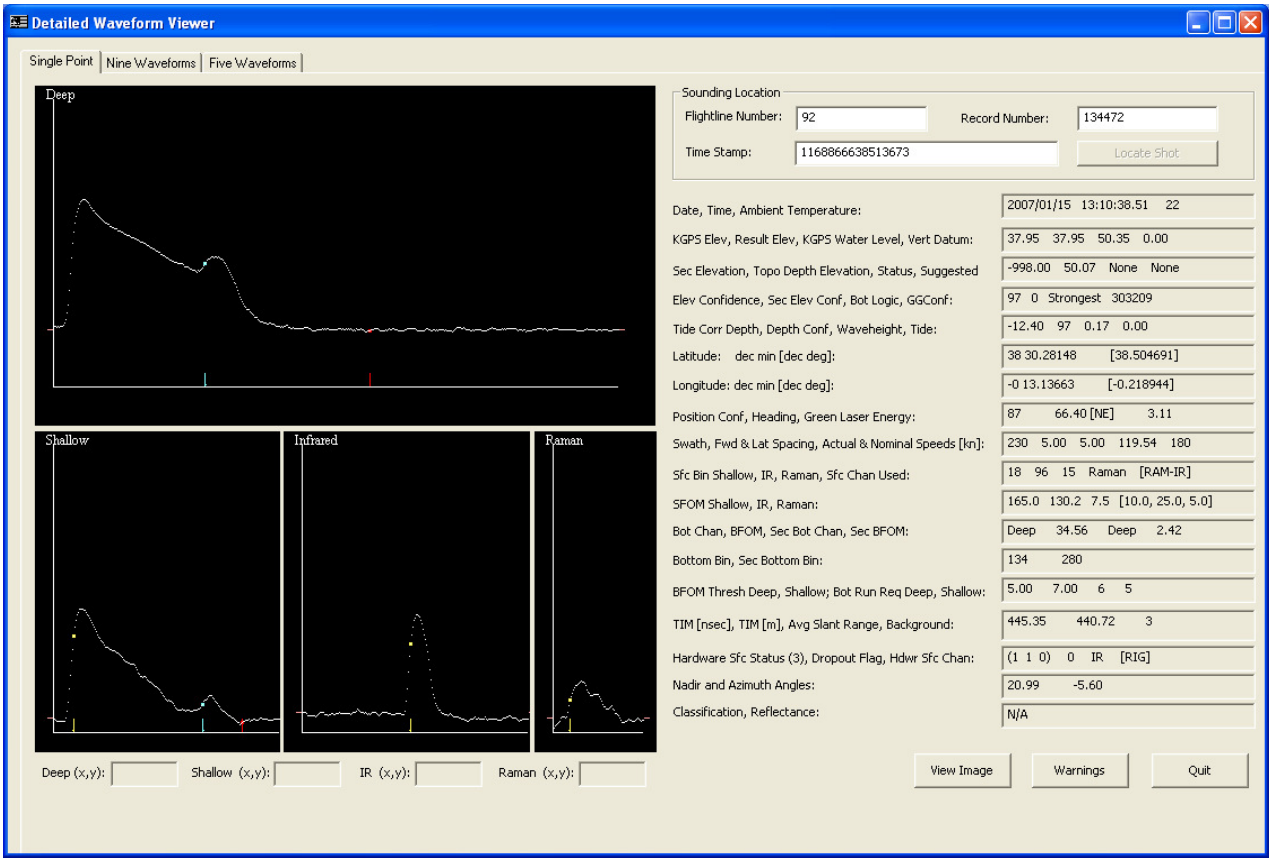


Figure 5 – SHOALS GCS Waveform Window

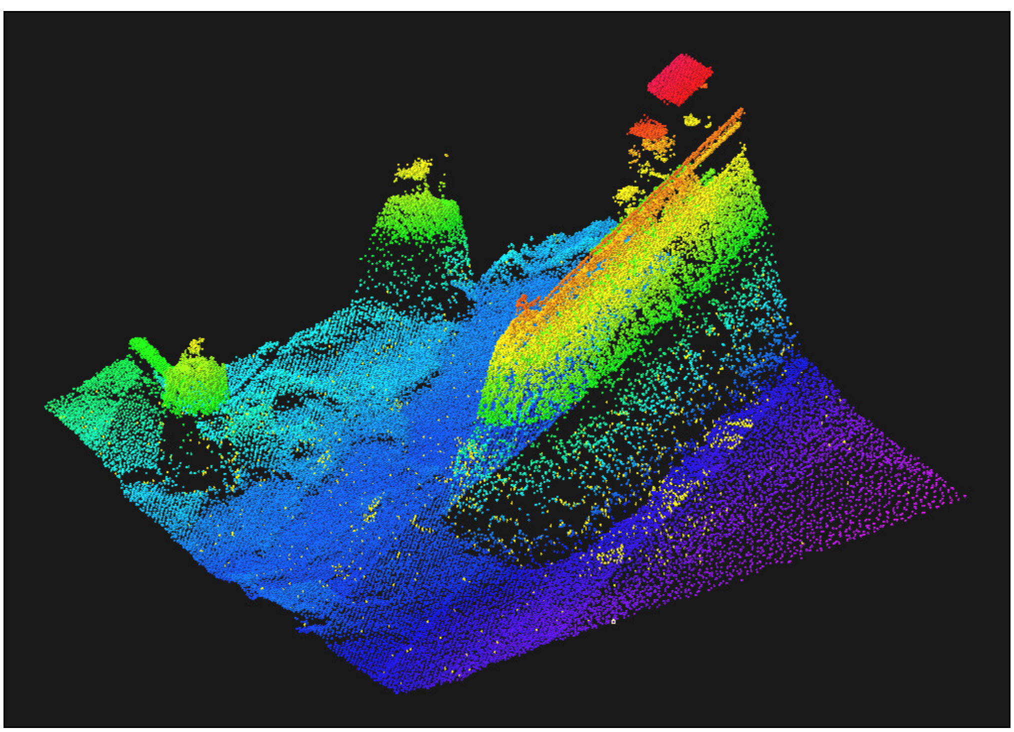


Figure 6 – Individual Soundings in 3D Editor

Figure 7 – Digital Image Viewer

A.3 SOFTWARE VERSIONS

System	Version	Remarks
Optech SHOALS	1.2	SHOALS Airborne System Operator GUI.
NovAtel Convert 4	3.9.0.7	Tool for conversion of binary NovAtel GPS data into RINEX format for processing in POSPac.
Applanix POSPac MMS	5.4	Position Orientation System Mobile Mapping Suite: Integration of precision GNSS with IMU inertial data for direct georeferencing of lidar point data.
Optech SHOALS GCS	6.32	SHOALS Ground Control System DAViS (Downloading Autoprocessing and Visualization Software) Module: for downloading, raw lidar processing, raw reflectance generation, data viewing, cleaning, and editing SHOALS data. MAPS (Management And Planning Software) Module: for creating flight lines, establishing data collection attributes for lines, and allocation of flight lines to a SHOALS Lidar Mission Plan.
IVS Fledermaus Pro	7.2.2	3D data visualization suite for geo-spatial editing, coverage reporting, quality control, and validation of hydrographic survey data.
FPI Workbench v5.00.05	5.00.05	Fugro Pelagos in-house toolset for raw Lidar data file analysis, flight line validation and tidal data application. An independent ArcGIS and ERDAS GUI, for coverage and planning, application of rotation matrices, image orthorectification, and quality control.
CARIS HIPS and SIPS	7.1	Bathymetric data processing software, primarily used for BASE Surface generation, feature selection, DTON compilation.
CARIS BASE Editor	3.2.0	Chart compilation software, primarily used for generation of S-57 feature files, constructing and editing contours and conducting ENC chart comparisons.
ENVI	4.7	Processing and analyzing geospatial imagery.
Optech REA	3	ENVI module for seafloor reflectance image processing.
ESRI ArcGIS	10	Project planning and management, spatial analysis, reporting, and quality control
ERDAS IMAGINE	9.3	Orthorectification and mosaicing of SHOALS digital imagery.
Global Mapper	11.00	Imaging software primarily used for converting '.tif' files to compressed '.ecw' format.

Table 1 – Software Versions

B. QUALITY CONTROL

B.1 LIDAR DATA PROCESSING

Data processing involves the following stages:

- In-field automatic data processing.
- In-field survey line acceptance by the Senior Data Analyst.
- In-field project wide review by the Lead Hydrographer.
- In-field rough cleaning by Data Analysts.
- Office-based validation of the data by Data Analysts.
- Office-based checking of the data by Senior Data Analysts and the Lead Hydrographer.
- QC of the data by the Lead Hydrographer.
- Approval of the data by the Lead Hydrographer once exported to CARIS.

B.2 DATA VALIDATION

During the field acquisition period, all data were inspected for coverage and overall quality at the field office. Preliminary field processing was conducted to ensure lidar measurements, imagery data, and positioning control met the project's quality requirements. Field processing also served to refine mission planning, particularly when external factors such as environmental and weather conditions impacted the daily operations.

At the conclusion of field operations, the survey data package was transferred to the FPI Datacenter in San Diego, where final processing and product assembly took place. The data processing flow is summarized below and in Figure 8.

- SHOALS data auto processing with KGPS
- Creation of ortho-mosaic imagery
- Data editing and validation
- Creation of reflectance imagery
- Application of observed tides through discrete zoning
- Data QC and approval
- Data import in to CARIS HIPS
  - Creation of BASE Surface, application of TPU
- Chart production
  - Rock selection
  - Contours
  - S-57 attribution
  - Chart comparison
- Deliverables QC and Approval
- Final Reports

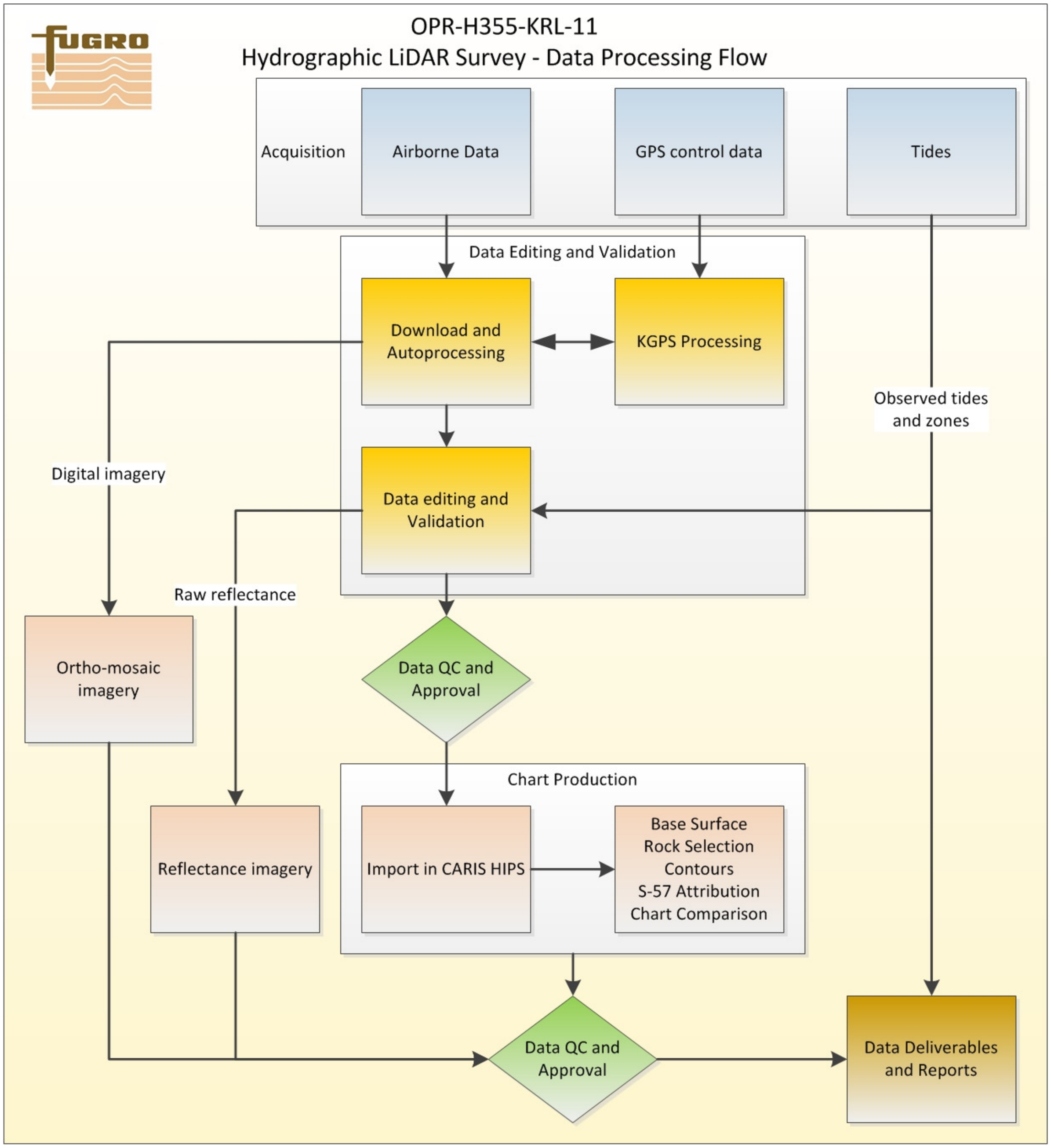


Figure 8 – Data Processing Flow

GCS integrated with Fledermaus creates PFM data files, which can be opened in Fledermaus for visualization and data review, and editing. Systematic selections of discrete data sections were reviewed using the 3D area-based editor. The 3D Editor opens up a smaller subset of data, displaying point clouds and allows the selection of individual soundings for editing.

In 3D Editor, editing tools like the waveform viewer, digital image viewer, and warnings messages were used by the data analyst to flag and validate depths based on quality indicators and metadata available in these windows. GCS re-processing tools are also available in the 3D Editor interface to enhance the data analyst's abilities to edit lidar depths. Such tools include, but were not limited to:

- Shallow water algorithm (SWA): recovery of very shallow depths (<1.5 m)
- Depth swaps: false bottom depth swapped in favor of valid bottom picks.
- False land: removal of false land hits caused by high energy returns (e.g. white water)

In large part, manual editing was used to remove gross fliers, obvious anomalies generally caused by poor water clarity and other non-bathymetric returns such as vegetation, boats and other floating objects.

B.3 TIDE APPLICATION

After datasets were edited and validated in GCS/Fledermaus, depths were reduced to survey datum with the application of observed tides data (stations 8724580 Key West and 8724671 Smith Shoal Light), as modified by final tide zoning.

As mentioned in preceding sections, lidar data were processed in KGPS mode for quality purposes. However, the GCS '.hof' file format is capable of retaining measured water depths generated during auto processing, so that raw depths can be reduced by the application of water level records. The actual application of tides and zones was implemented in FPI's Workbench toolbox software, making use of the JOA supplied water level records files and the Zone Definition File. In essence, the lidar shot timestamp and position are used to locate the tide water level intervals, apply the time zone offset, interpolate between 6-minute tide readings and apply the applicable zone range ratio. Manual point checks by data analysts were performed throughout the survey area to verify correct computations.

B.4 QC

The Lead Hydrographer and Senior Data Analysts performed final QC of data at various stages during the data processing (single flight dataset editing, combined dataset editing, following tide application, etc.). Recurrent data editing / QC cycles had to be implemented to maximize editing best practice and minimize involuntary oversight. The final editing approval was the first step toward production of Sheet deliverables.

B.5 APPROVAL

All quality controlled data was exported from GCS for spatial presentation and final approval in CARIS by the Lead Hydrographer. A BASE Surface for each registered sheet was created and the following items were checked for correctness / completeness against the SHOAL layer:

- All applicable flight lines were exported.
- Horizontal and vertical TPU was assigned correctly.
- Data range of minimum and maximum depth values were within project bounds.
- The BASE Surface completely covers the NOAA sheet limits.
- There were no unexplained gaps in the final coverage.
- A standard deviation surface was reviewed to ensure all data meets the accuracy specifications.
- A density surface was reviewed to ensure 200% coverage has been achieved across the area (where water clarity / water depth has permitted full 200% coverage).

B.6 DIGITAL IMAGERY PROCESSING

Digital RGB images were exported from packaged format in GCS into individual frame images in .jpg format. During export, each 1600 x 1200 pixels frame was provided with timestamp, position and orientation information from the SBET KGPS solution. This information was used to create the rotation matrices required in the rectification process conducted in ERDAS software v9.3. No DEM was used in the rectification process; instead a constant elevation simulating the sea surface was supplied.

The rectified imagery was analyzed for general image quality and further enhancements. Common situations where imagery required additional processing included:

- Dark imagery due to existing conditions at time of survey (twilight, clouds)
- Bad timestamps that produced incorrect geo-registration of individual frames
- Reversing order of overlapping line imagery to minimize sun glint

FPI in-house software was used for the final mosaic creation. Feathering on the frame overlap was applied but no color correction, balancing or other processes were used in the mosaic production in order to preserve, as far as possible, an original and unaltered image description of surface conditions.

B.7 REFLECTANCE DATA PROCESSING

During the auto processing of each flight dataset, raw bottom reflectance data (BRF) were produced for each line. After completion of the editing work, the BRF files were updated to reflect the validated bottom returns. Then these BRF files were taken to Optech's REA software that runs as an add-in module in ENVI software v4.7. REA exclusively processes SHOALS data to produce reflectance imagery. Imagery was exported as 32-bit geotiff files for display and analysis on common GIS software. REA processing is described in the following paragraphs.

Imagery for each flight dataset was created, based on a min/max water attenuation coefficient and shallow water segment threshold. Using a radiative transfer equation, the measured lidar signal is expressed as a function of the transmitted energy, imaging geometry, and physical environment. This equation is inverted to solve for seafloor reflectance for each pulse. This procedure yields an estimate of reflectance at each location where the depth is measured.

Images are produced from the point cloud by rasterizing the reflectance values into the same grid used to generate the digital surface model of the seafloor, normally at the data density collected, in this case, a 3m cell size. In this way, the reflectance image is perfectly registered to the 3D model of the seafloor.

The resulting dataset images were brought in to ArcGIS to build balanced gray-scale mosaics. Final rendering is preserved when converting mosaic imagery to an 8-bit Geotiff format. The Geotiff imagery was then exported as an ASCII XYZ file, where the 'Z' field represents the 0-255 scaled relative reflectance value.

B.8 DATA MANAGEMENT

B.8.1 Survey Line Identification

Block	Line Identifier	Sounding Density (m)	Line type	Remarks
Block 1 – 100%	6 - 29, 68 -76	4x4	Main Scheme	Northern lines substituted to S of Block 1 (1-5 → 68-76).
Block 1 – 200%	35 - 67	4x4	Main Scheme	Northern lines substituted to S of Block 1 (30-34 → 60-67).
Block 2 – 100%	1 - 21	4x4	Main Scheme	Southern lines substituted to S of Block 3 (22-31 → 81-99).
Block 2 – 200%	32 - 52	4x4	Main Scheme	Southern lines substituted to S of Block 3 (53-62 → 61-80).
Block 3 – 100%	1 - 30, 81 - 99	4x4	Main Scheme	
Block 3 – 200%	31 - 80	4x4	Main Scheme	
Block 4 – 100%	1 - 31	4x4	Main Scheme	
Block 4 – 200%	32 - 63	4x4	Main Scheme	
Block 5 – 100%	1 - 25	4x4	Main Scheme	
Block 5 – 200%	26 - 50	4x4	Main Scheme	
Block 6 – 100%	1 – 25	4x4	Main Scheme	
Block 6 – 200%	26 - 50	4x4	Main Scheme	
Block 7 – 100%	1 – 25	4x4	Main Scheme	
Block 7 – 200%	26 - 50	4x4	Main Scheme	
Block 8 – 100%	1 – 25	4x4	Main Scheme	
Block 8 – 200%	26 - 51	4x4	Main Scheme	
Refly	Multiple	4x4	Refly Lines	Lines designed to fill gaps in poor water clarity areas.
Cross Line	Multiple	4x4	Cross and Examination Lines	For relative vertical accuracy checks. Majority of cross lines planned over small features requiring lidar examination.
Ground Truth	10	4x4	Dynamic Position Check and TPU	For absolute horizontal accuracy checks and Total Propagated Uncertainty determination.

Table 3 – GCS Survey Line Identifiers

B.9 ERROR MINIMIZATION AND MODELS

B.9.1 Water Clarity

The greatest contributor to depth performance, seabed coverage and data quality with a lidar system is water clarity. In order to address this concern FPI conducted water clarity assessments across the project area, from the planning phase through to the final flight, using a number of different techniques.

B.9.2 Water Clarity Assessment - Remotely Sensed Data

During the planning phase of the project remotely sensed data was used to estimate the expected water clarity conditions for the Florida Keys project area and the likely depth penetration of the SHOALS-1000T, as follows:

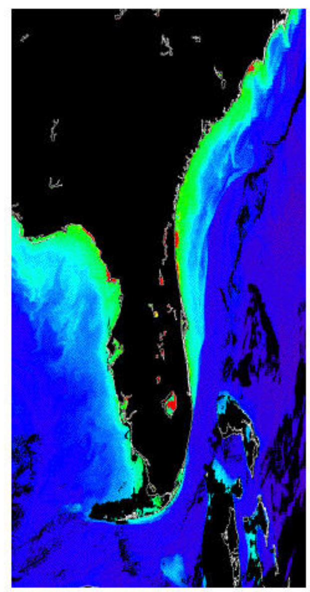
The diffuse attenuation coefficient at band 3

K490 indicates the turbidity of the water column - how visible light in the blue - green region of the spectrum penetrates within the water column . It is directly related to the presence of scattering particles in the water column.

$$K(490) = K_w(490) + A\left[\frac{L_W(\lambda_1)}{L_W(\lambda_2)}\right]^B,$$

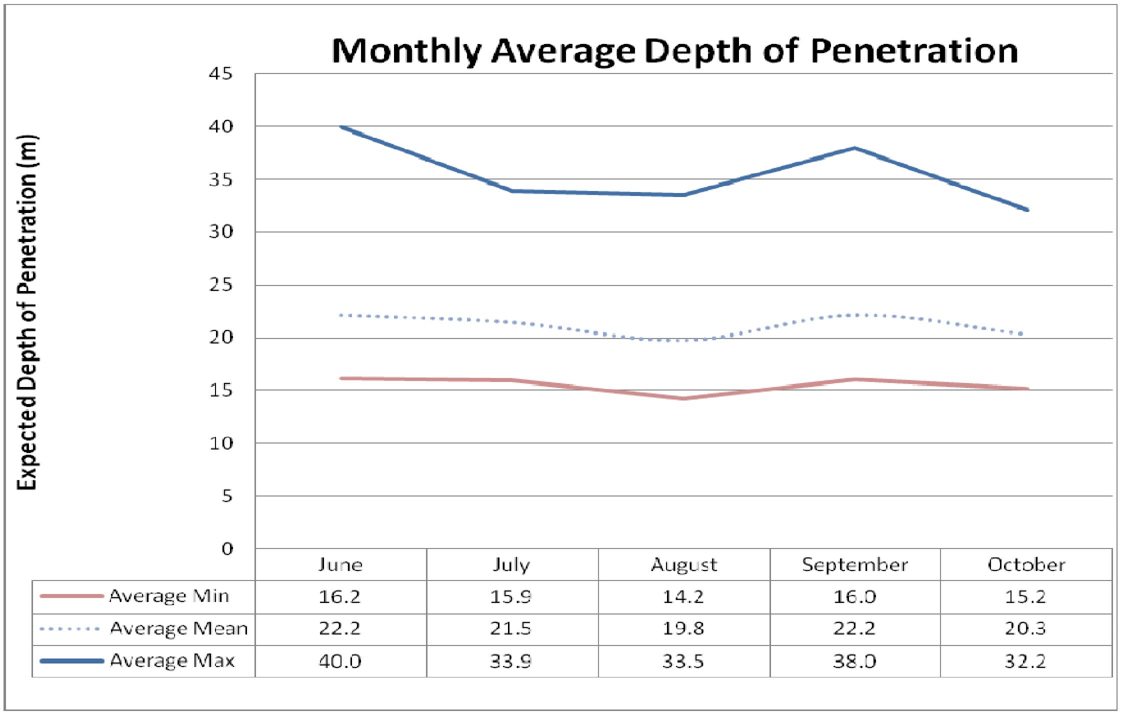
$K_w(490)$ = the diffuse attenuation co for pure water = 0.016 m^{-1}
(From Mueller 2000 and Smith and Baker 1981)

lambda1 = 488/490
lambda2 = 551/555
A = 0.15645
B = -1.5401



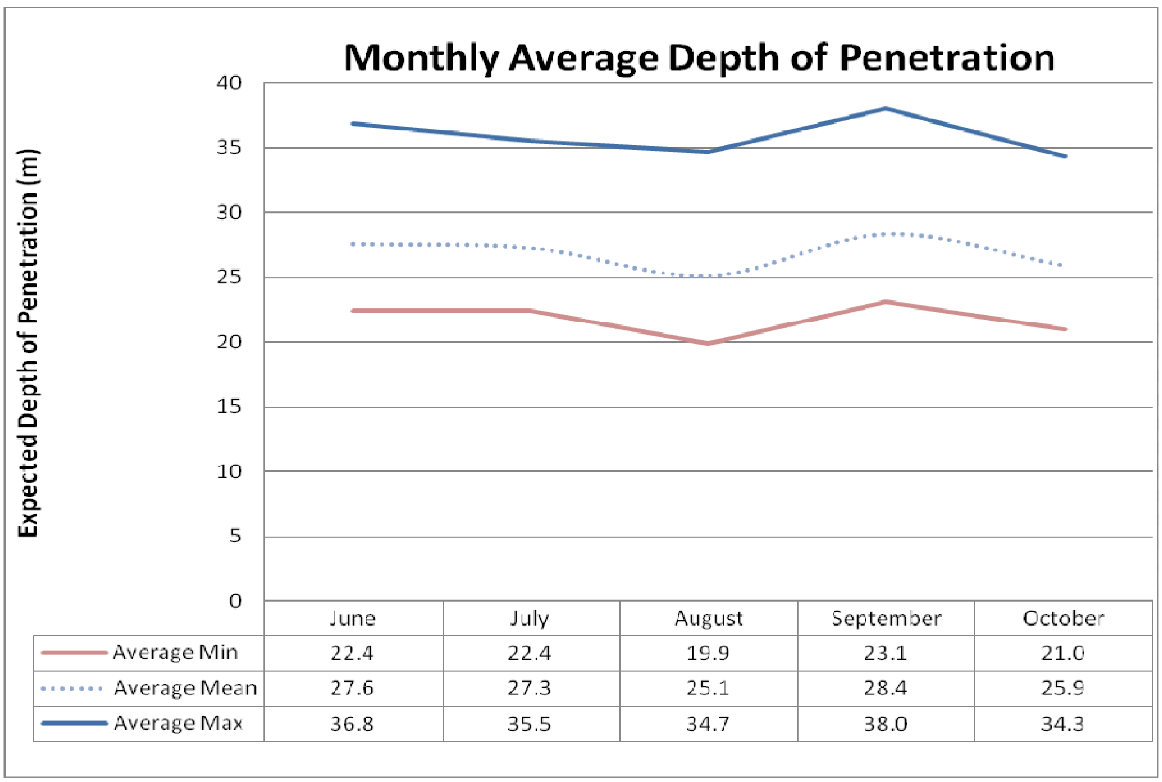
Level 2 metadata:
K_490: slope = 0. 0002
K_490: intercept = 0

Figure 9 – The K490 Equation



	June	July	August	September	October
Average Min	16.2	15.9	14.2	16.0	15.2
Average Mean	22.2	21.5	19.8	22.2	20.3
Average Max	40.0	33.9	33.5	38.0	32.2

Figure 10 – Depth Penetration Estimates from K490 – OPR-H355-KRL-11 East



	June	July	August	September	October
Average Min	22.4	22.4	19.9	23.1	21.0
Average Mean	27.6	27.3	25.1	28.4	25.9
Average Max	36.8	35.5	34.7	38.0	34.3

Figure 11 – Depth Penetration Estimates from K490 – OPR-H355-KRL-11 West

B.9.3 Water Clarity Assessment - Reconnaissance

On the 29th and 31st of August and 1st and 2nd of September, 2011, water clarity observations were conducted by Fugro Pelagos, Inc. (FPI) staff in the Key West National Wildlife Refuge and surrounding areas of the Florida Keys National Marine Sanctuary. Secchi disc, visible depth measurements were recorded at moments of opportunity during the JOA establishment of a subordinate tide station at Smith Shoal Light and deployment of a bottom mounted tide gauge at the Quicksands and in the vicinity of Boca Grande Key. A 31' Yellowfin center console power boat was chartered from "TailChaser Charters" in Key West, FL to perform the tides work and conduct water clarity measurements. The primary objectives were to take Secchi disc (45cm diameter) measurements within the FPI proposed survey area and to assess possible areas of concern for future Lidar data collection.

The weather conditions were generally calm, with overcast to partly cloudy skies, and winds of 11 knots – gradually shifting from the west to the east through the week. The Beaufort Sea State average during the entire collection was 3.

A total of 23 measurements were taken. Overall, the water appeared clear throughout the proposed survey area, with reduced water quality to the north near Smith Shoal Light. The collection sites and results are provided in full at Appendix III.

B.9.4 Water Clarity Assessment - Diver Reports

On October 4, 2011, Brian Walker, Research Scientist with the National Coral Reef Institute, Nova Southeastern University, provided the following diver visibility reports from the Marquesas Keys. The observations were taken the previous week. Brian noted that "water was clearest over the shelf edge reef during incoming high tide". This information proved very useful in the early stages of the project, before a clear understanding of water clarity dynamics had been derived from ALB Data Acquisition.

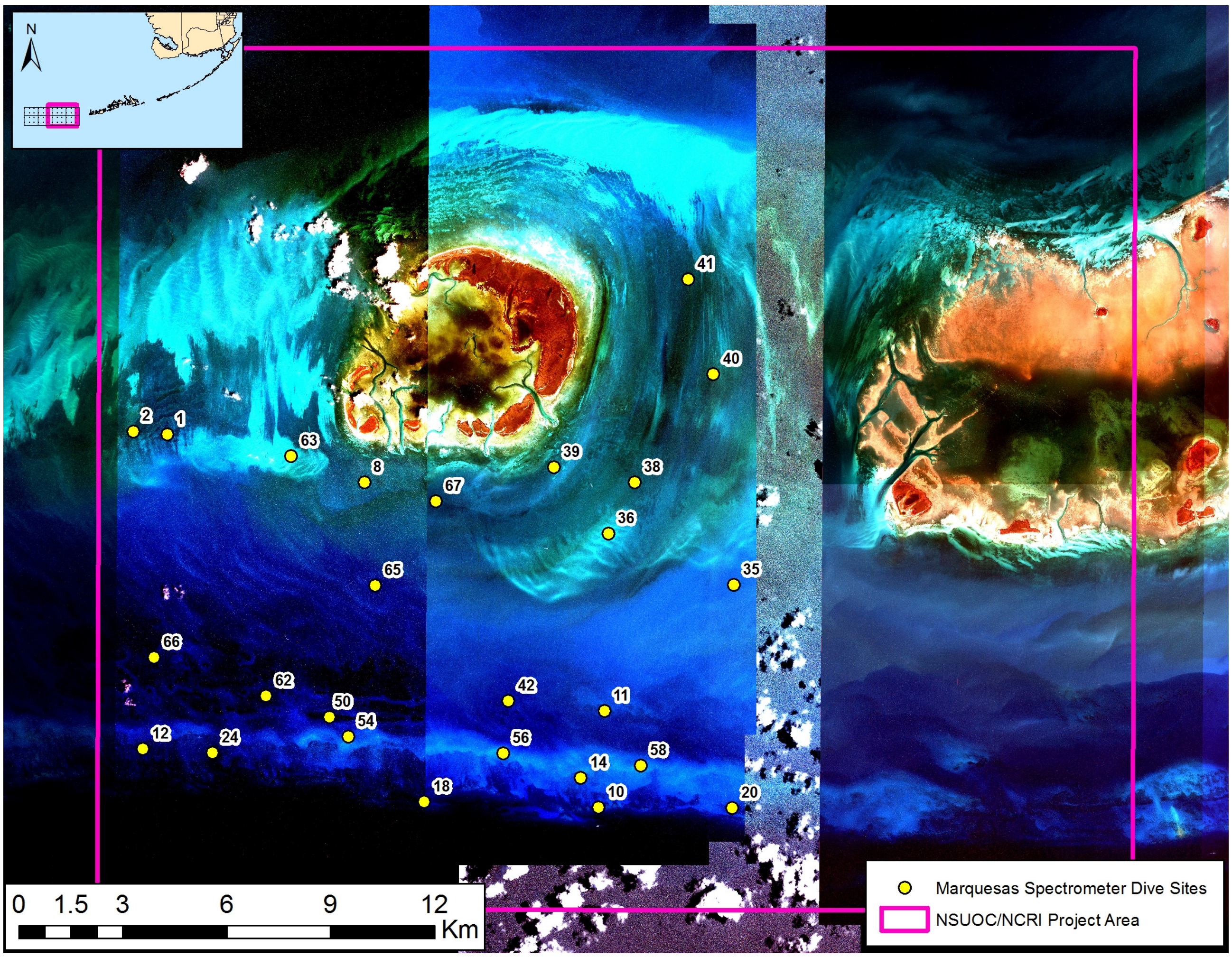


Figure 12 – NCRI Dive Sites from Late September 2011

Id	Latitude (DM)	Longitude (DM)	Map Cover	Diver-estimated Visibility (in feet)
1	24 32.87838	82 12.97044	SEAGRASS >90%	10
2	24 32.92218	82 13.54782	SEAGRASS >90%	10
8	24 32.15634	82 09.59442	LIVE CORAL 50-90%	30
10	24 27.11184	82 05.54886	LIVE CORAL 50-90%	50
11	24 28.6185	82 05.46162	LIVE CORAL 50-90%	30
12	24 27.96552	82 13.34124	LIVE CORAL 50-90%	30
14	24 27.57204	82 05.85276	MACROALGAE 50-90%	50
18	24 27.17652	82 08.5257	LIVE CORAL 50-90%	30
20	24 27.11586	82 03.26814	LIVE CORAL 10-50%	50
24	24 27.91218	82 12.1491	LIVE CORAL 10-50%	50
35	24 30.6045	82 03.2655	UNCOLONIZED >90%	3
36	24 31.38672	82 05.41716	UNCOLONIZED >90%	10
38	24 32.19084	82 04.97562	SEAGRASS >90%	10
39	24 32.41236	82 06.35502	SEAGRASS >90%	10
40	24 33.88584	82 03.64176	SEAGRASS 50-90%	10
41	24 35.36358	82 04.09002	SEAGRASS 50-90%	10
42	24 28.76154	82 07.10028	LIVE CORAL 50-90%	30
50	24 28.48896	82 10.15962	LIVE CORAL 50-90%	30
54	24 28.18716	82 09.83184	UNCOLONIZED >90%	10
56	24 27.94134	82 07.1814	UNCOLONIZED >90%	30
58	24 27.77076	82 04.83072	UNCOLONIZED >90%	50
62	24 28.80486	82 11.24364	SEAGRASS >90%	10
63	24 32.55774	82 10.8465	UNCOLONIZED >90%	10
65	24 30.54396	82 09.39204	UNCOLONIZED >90%	10
66	24 29.39268	82 13.15884	LIVE CORAL 50-90%	15
67	24 31.86936	82 08.37102	LIVE CORAL 50-90%	10

Table 4 – NCRI Dive Site Locations and Estimated Visibility

B.9.5 Water Clarity Assessment - ALB Data Acquisition

The water clarity varied significantly, both spatially and temporally across the project area. Poor water clarity was mainly driven by moderate to strong winds, particularly from the north-east. It was apparent that high rainfall and certain tide cycles also played a major role in deteriorating water clarity conditions.

During the 35 day data acquisition period there were only 8 days that were considered to be ideal for ALB data acquisition across the majority of the project area. Even on those optimal weather and water clarity days a persistent turbidity plume was present across the project area, extending from the Northwest Channel, down through the Southwest and West Channels, right out to southwest of the Marquesas Keys. It became apparent that only sparse, poor accuracy data could ever be hoped to be acquired in the centre-east of the project area. It was obvious that there would be expansive areas of no lidar coverage due to very poor water clarity.

This was communicated to the NOAA COTR during his field-site visit to Key West in mid-October. Two separate substitution plans were officially proposed and approved by the COTR, the first on October 26 and the second on November 1, 2012. The general principle of the substitutions was to remove flight lines from West Channel and add southern extensions to the H12377 and H12380, where water clarity was generally good under all environmental conditions. The budgeted *time* taken to survey the removed lines was calculated and applied to the number of lines to be flown in the southern extensions. This is why the substituted flight lines are shorter (to fit the general charted bathymetry), but there are significantly more of them.

The resultant removal / addition of flight lines due to persistent poor water clarity are demonstrated in the following graphic. The yellow polygons relate to Substitution 1 and pink polygons Substitution 2. The underlying interim bathymetry coverage image in this graphic demonstrates the difficulty in acquiring good quality data in West Channel during October.

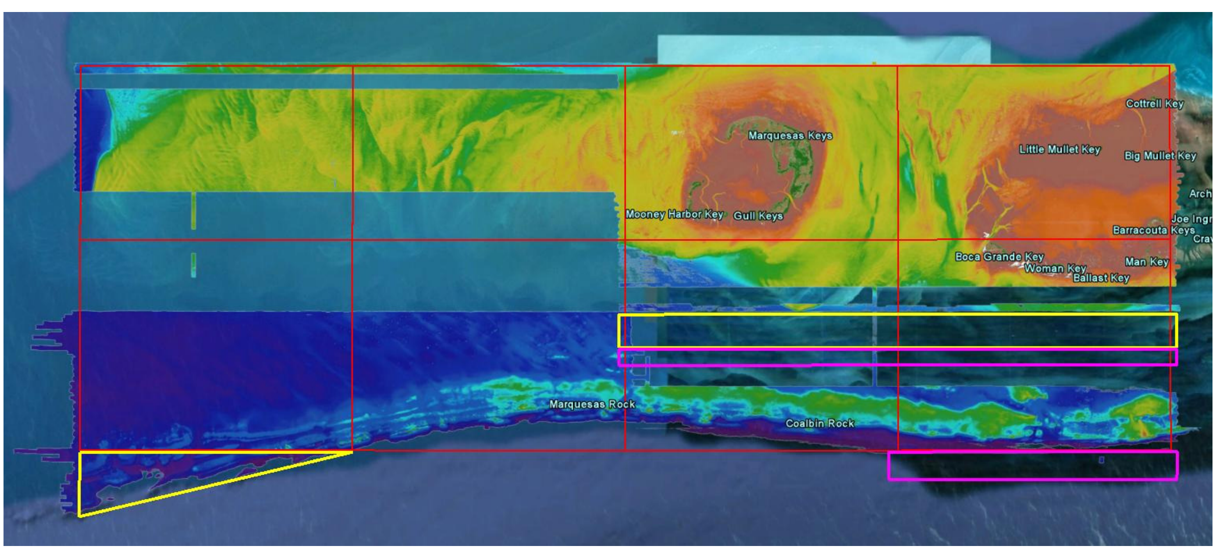


Figure 13 – OPR-H355-KRL-11 Approved Substitution Areas for Poor Water Clarity

Even with the worst water clarity area substituted there were still large areas of no, or limited, lidar seabed coverage, due to turbid water conditions. Despite flying many of these areas on 4 or even 5 occasions, the coverage could not be significantly improved. In some highly dynamic water clarity areas the first 100% coverage pass yielded good results. However, subsequent 200% flight lines and then refly lines only added sparse, in-accurate data to the final coverage. In a number of such instances the 200% coverage and refly data was completely rejected to adhere to the project accuracy specifications. Special regard was given to shoaler features across these turbid seabed areas, and in some cases 'noisy' data was accepted to ensure significant seabed objects were rendered as part of the survey.

For the project to be successful, water clarity had to be managed very closely throughout the data acquisition period. Priority area management ensured that the system was operating in the correct area at the correct time. In general, the water clarity in the southern areas remained good to very good. These areas were typically targeted when the north was extremely turbid. When the northern areas did clear, data acquisition efforts were maximized and, with two flight crews, up to 4 sorties per day were being flown. Data analysis, following each flight, also revealed that best data was often acquired around the high tide period, particularly during Spring tide cycles. Persistently poor to marginal water clarity areas were specifically targeted during high Spring tides to maximize final seabed coverage.

In order to minimize the errors and data gaps attributed to poor water clarity across the entire project area, ongoing analysis of the water column conditions from each survey flight was imperative.

B.9.6 Total Propagated Uncertainty

A total propagated uncertainty (TPU) line was designed and flown on 16 separate occasions in order to determine the repeatability of the SHOALS-1000T system and assign accurate vertical TPU for all depth data acquired throughout the project. The results of the mean depth differences and standard deviations of gridded surface comparisons are presented below:

TPU Area Name	Raw Depth (m)	Flight Lines Compared	Mean MDD + 2 SD (m)
TPU1	2	14	0.32
TPU2	3.5	8	0.27
TPU3	5	7	0.36
TPU4	8.5	15	0.35
TPU5	10	13	0.35
TPU6	14.5	6	0.37
TPU7	22	12	0.52
TPU8	32	4	0.39

Table 5 – TPU Area Depth Comparison Results

As ALB data accuracy is related to depth, the benchmark area depths were plotted against the MDD + 2SD value observed at each location.

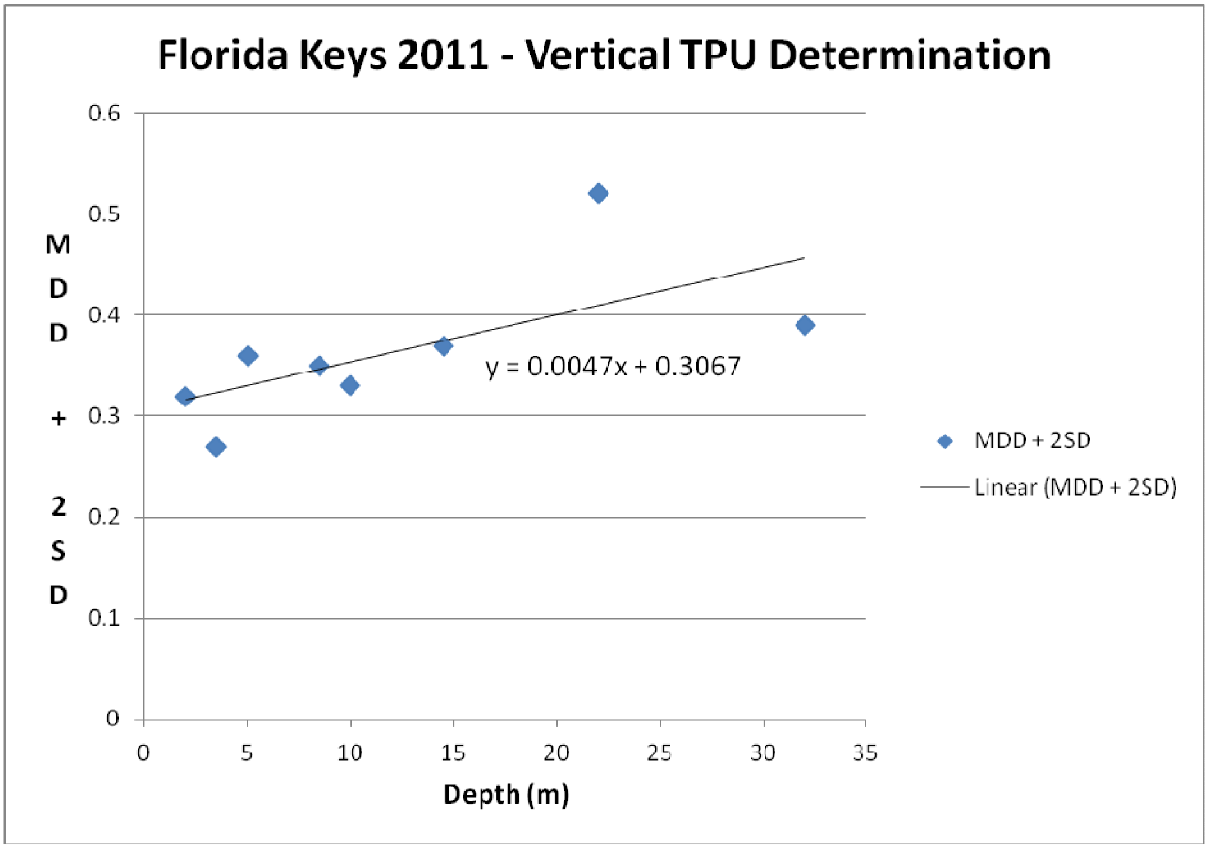


Figure 14 – Vertical TPU Determination

For simplicity, the relationship between depth and data accuracy was considered linear and a trendline was fitted to the scatter plot. The resultant equation was derived for vertical accuracy of the OPR-H355-KRL-11 project:

$$Y = 0.0047x + 0.3067$$

The horizontal TPU for the project was also derived from actual results of the survey, being the dynamic navigation position check comparisons. The mean difference (MD) between the observed and surveyed check point positions was 2.331m with a 2 sigma standard deviation of 2.250m. That results in a value of 4.580m for MD + 2SD and 0.081 for MD – 2SD. Thus, the final horizontal TPU value for all soundings across the project has been assigned as 4.449m.

The final look-up table used for assigning vertical and horizontal TPU to the CARIS BASE Surface was as follows:

Depth	Vertical TPU (m)	Horizontal TPU (m)
-50	0.307	4.499
0	0.307	4.499
2.5	0.318	4.499
5	0.33	4.499
7.5	0.342	4.499
10	0.354	4.499
12.5	0.365	4.499
15	0.377	4.499
17.5	0.389	4.499
20	0.401	4.499
22.5	0.412	4.499
25	0.424	4.499
27.5	0.436	4.499
30	0.448	4.499
32.5	0.459	4.499
35	0.471	4.499
37.5	0.483	4.499
40	0.495	4.499

Table 6: Vertical and Horizontal TPU Look-up Table

However, when the calculated grid node standard deviation was greater than the assigned vertical uncertainty, the SD is used as the uncertainty value. This has occurred in areas of high relief, which is common throughout the survey area. In some cases the standard deviation may exceed IHO Order-1 limits. This could be attributed to the seabed gradient and a 3m grid resolution being used.

B.10 DATA OUTPUT AND DELIVERABLES

A directory listing of each digital deliverable is provided at Appendix II.

C. CORRECTIONS TO SOUNDINGS

The only offset measurement required during system mobilization was from the POS/AV Inertial Measurement Unit (IMU) to the POS AV GPS antenna. The IMU is completely enclosed within the laser housing. The offsets from the IMU to the common measuring point (CMP) on the outside of the housing are known constants.

Offsets were measured using a total station establishing a base line along the port side of the aircraft. Ranges and bearings are measured from the total station to the CMP on the top of the laser housing. Additional measurements are made to the sides and top of the housing to determine its orientation. A final measurement is made to the center of the POS/AV GPS antenna. The IMU to POS/AV GPS offsets are calculated using the known IMU to CMP offsets. A summary of the offset measurements made during system mobilization are presented below. The offsets from the IMU to the POS AV GPS antenna are entered into the POS/AV console prior to survey.

SENSOR REFERENCE POINT to GPS ANTENNA		SET 1		SET 2		SET 3		SET 4	
	X	1.645	REJECT DATA ☐	1.644	REJECT DATA ☐	1.645	REJECT DATA ☐	1.645	REJECT DATA ☐
	Y	-0.140		-0.143		-0.139		-0.140	
	Z	-0.857		-0.862		-0.858		-0.857	

TAPE MEASUREMENT (SENSOR REF to GPS ANTENNA)	
X	1.676
Y	-0.162
Z	-0.815

IMU to SENSOR REFERENCE		SENSOR REF to GPS ANTENNA	
X	0.073	X	1.645
Y	-0.230	Y	-0.141
Z	-0.415	Z	-0.859

IMU to GPS ANTENNA		
	X	1.718
	Y	-0.371
	Z	-1.274

Checked By: D.Tobin- 5/8/11

Figure 15 – SHOALS Sensor Offsets

D. APPROVAL SHEET

LETTER OF APPROVAL – OPR-H355-KRL-11

This report and the accompanying Fugro Pelagos, Inc. survey deliverables are respectfully submitted.

Field operations contributing to the accomplishment of this survey were conducted under my direct supervision with frequent personal checks of progress and adequacy. This report and the accompanying Fugro Pelagos, Inc. survey deliverables have been closely reviewed and are considered complete and adequate as per the Statement of Work and Hydrographic Project Instructions.

Report	Submission Date
Data Acquisition and Processing Report	March 16, 2012

Scott Ramsay
Hydrographer
Fugro LADS, Inc.

Date: March 16, 2012